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POLE CHANGE TYPE SALIENT-POLE GENERATOR-MOTOR FOR KUROMATAGAWA NO. 2 POWER STATION, ELECTRIC POWER DEVELOPMENT CO., LTD.

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I. PREFACE

The pole change type generator-motor which is considered to be one of the most useful machines of the pumping power generation, was rarely used in our country. More than twenty years have elapsed since the erection of the first pole change type salient-pole water wheel generator of rated capacity 20 Mva 44/36 pole at Hohenwarte Power Station, Germany. During these years theories, especially for pole-change type salient-pole synchronous machines, have taken remarkable strides developing finally to our Fuji pole-change type synchronous machine. (Reported on in the Fuji Denki Review.[1])

The reasons why the actual examples are so few is because the pumping power generation has only recently been adopted, consequently, pumped storage power stations themselves are few in number.

Furthermore, because the output of the generator-motor for pumping has been very great, users have hesitated in accepting the pole change type because of these few examples although they understand that theoretically it is good.

By the development of the pump turbine, the disparity between the speeds at which maximum efficiency is attainable during the water wheel operation and the pumping operation has been lessened. On the other hand, to operate one runner for two purposes results in considerable low efficiency on one side of the operations.

The purpose of the pumping power generation is to obtain the most effective overall power generation so that any lowering in efficiency is a fatal factor toward this aim and greatly influences the pumping generation itself.

Therefore, the merits of the pole change type should be emphasized more and more along with the development of the pumping power generation. With forethought we manufactured the pole change type of a rather large capacity extending our theoretical studies to model machines. This may solve the problems anticipated and aid the users in recognizing the merits of this type. Our tests proved that this machine is quite reliable and we are happy to report the successful results of the pumping station project.

In this report, we present an outline of the generator-motor and describe the test results in detail, including such factors as the influence of higher harmonics, utilization factor of flux, and vibration and local heat. These results substantiate the theory behind this type of generator-motor and thus should allay any concern on the part of the purchaser.

II. RATING

This power station is a pumped storage power station having the Kuromatagawa No. 1 dam down stream and having water pumped up to the No. 2 dam.

The operation schedule consists of an annually regulated power flow by discharging the storage water of the No. 2 dam regularly and having water pumped up at midnight and noon, although the operation time differs somewhat seasonally.

Table 1 shows the rated specifications of this machine. It operates at 300 rpm for gnenrator sequence, 333 rpm at pump heads above 60 m. and 300 rpm at pump heads below 60 m for motor sequence utilizing the full merits of the pole-change type. Since the head in this power station varies considerably it is impossible to attain maximum overall efficiency if the runner is operated at one speed. So

Table 1 Rating

	Generator operation	Motor operation	
Output	19,000 kva	20,500 kw	19,000 kw
Voltage (v)	11,000	10,500	10,500
Current (amp)	997	1159	1075
Power factor	0.9	1.0	1.0
Frequency (c/s)	50	50	50
Speed (rpm)	300	333	300
Poles	20	18	20

dividing the range of the variable head into two phases, the machine is operated at 300 rpm, 20 poles at a low head, thus a high overall efficient operation of the pump head is possible.

Regarding the terminal voltage in each operation, voltage at the primary substation were taken as the base since they are maintained relatively constant. As a result, 11 kv ± 5% for generator operation and 10.5 kv ± 5% for motor operation are enough for basic operational voltage when the main transformer with a no load tap-changer of 161–154–147 kv/10.7 kv was used and taps of 161/154 kv were changed seasonally. Because an excess current flows at only about 5% even when on load tap-changing devices were not provided, we adopted 11/10.5 kv as the rated voltage of the generator-motor and the three-step tap-changer was provided for the transformer.

Fortunately, the same magnetic loading can be obtained by the terminal voltage of 11 kv at 20 pole and 10.5 kv at 18 pole although these were derived independently for the utilization factor of flux for each pole.

III. POLE CHANGE METHOD AND OPERATIONAL CONDITIONS

160 kv is supplied from the primary substation when the generator-motor operates as the motor. For starting, the half-voltage self-start method is used providing 50% voltage tap for the main transformer and the so-called "Maglager"—our special magnetic thrust bearing which reduces the static friction torque of thrust bearing—is also used. Here we didn't use the part-winding start method because a double-wye connection couldn't be made in an armature winding of one-turn coil according to the rated voltage and output.

Generally in the Deriaz turbine counter torque is reduced considerably by simply laying down its blade thus we can avoid the troublesome method of the Francis type turbine whereby the water level is reduced and the runner is rotated in the air. Of course, the pull-in torque is greater than the value obtained by the Francis type running in the air so that it is difficult to suppress the starting kva lower than half the rated kva (as in the case of the Francis turbine.) In this machine, starting kva is being suppressed near the rated kva even when it is started at any pole of 20 or 18.

The GD^2 of this machine is large corresponding to the acceleration time of 8.9 sec. The natural GD^2 corresponds to 5.0 sec in acceleration time so that about 80% GD^2 is added to the requirement of the hydraulic machine. Therefore, special caution must be directed to the damper winding of the pumping generator motor which receives severe thermal stress during acceleration. In this case, damper winding is so designed that a temperature rise is restrained under 150°C to offset the twice repeated startings.

It was presumed by the test of the pump that counter torque at pull-in might be 2000 kw. The value is extremely large compared with the Francis type turbine. For example, this loss was only 1400kw at a 54.5 Mw generator-motor previously manufactured and coupled with the Francis type, whereas, in this case of 20.5 Mw the loss amounts to 2000 kw, thus, synchronisms may be difficult because of the great loss produced by the runner in the water. However, the fact that a self-start can be made by simply controlling the blade in the Deriaz type without depressing the water level is of great merit. Utilizing this, the change-over to full voltage before synchronization is generally adopted to alleviate the difficulty of synchronization.

In this machine, because pull-in torque at half-voltage approaches the limit for pull-in and counter torque has almost no allowance, automatic change-over to full voltage is employed when it is accelerated to the minimum slip obtainable by half-voltage starting.

Rush current, which is when the voltage is changed-over, consists of the asymmetrical current due to residual voltage and symmetrical current as the induction motor. Asymmetrical rush current can be suppressed at any phase by using a time limit relay, the time from open to full voltage reclose being adjusted and reclose after the residual voltage being damped. Symmetrical rush current as the induction motor is decided by a slip at change-over. In this machine it is accelerated 1% below the slip by a half-voltage start. Since the current at full voltage is low and soon damped by acceleration the symmetrical rush current is insignificant.

After synchronization it operates at a constant output decided by the head at that time. As previously mentioned the voltage can be changed ±5% of the rated voltage a constant output considering excess current may be excited when the voltage is lowered. The on load tap-changer for the main transformer has been omitted.

The pumping operation is made not only at midnight but also at noon in order to recover the surplus power. During the one hour operation at noon, the change-over time for generator⇆motor must be shortened to obtain a net pumping time. One way to shorten braking time is to use a dynamic brake. However, in this Deriaz type machine stopping is made quickly without using the above but rather because of braking action caused by eddy loss, the latter due to the standing blade.

The utilization factor of flux at the pole-change machine is achieved in two ways. One is to distribute poles with different pole-pitch, considering that the magnetic flux component of many desired poles reaches maximum. However, in this method, the utilization factor of flux lowers when the number of poles is increased and also this method is difficult in mechanical construction. The second way is to have more than the desired number of poles distributed and the component of each pole made maximum by changeing the connection using the distributed winding field most effective.

As previously reported,[1] the Fuji pole change system belongs to the latter case, that is, mechanical strong poles, large and small, are distributed maintaining the magnetic and mechanical balance. This then is the best method for utilizing the flux.

Fig. 1 shows the distribution of poles and the magnetic field of our plan in which we gave the utmost consideration to the high utilization factor of flux and minimizing the number of small poles.

In *Fig. 1*, (a) illustrates the distribution of pole, (b) the distribution of the magnetic field at 20 poles, and (c) the distribution of the magnetic field at 18 pole. The ratio of maximum flux density of the field component at 18 and 20 poles is as follows:

$$B_{20} : B_{18} = 1 : 0.865$$

Needless to say, many higher harmonic fields exist besides this fundamental component as is discernible from *Fig. 1*.

To eliminate the higher harmonics component from the induced voltage wave, adequate winding connection and winding factor must be selected. Winding connections are complicated because the connection change of pole-change 10 : 9 is difficult. If we avoid this troublesome effort, the induced voltages at each winding will neutralize each other by their differences in vector, thus the effective field itself is not being utilized for building the voltage.

Fig. 2 shows these complicated winding connections but they do not appreciably influence insulation and ventilation. From these winding connections we can amass the windings of the uni-directional vector raising the utilization factor of the fundamental wave component. As we mentioned earlier, the change-over of the armature winding to each pole is easily made by using the change-over switch provided at the outside terminals.

The ratio of the winding factor at 18 and 20 poles is as follows:

$$\xi_{20} : \xi_{18} = 1 : 0.98$$

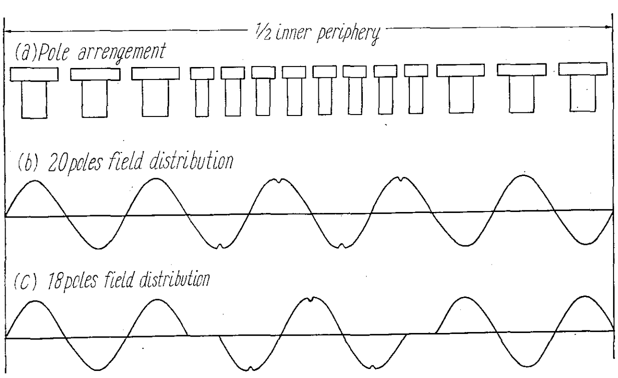

Fig. 1 Poles and magnetic field distribution

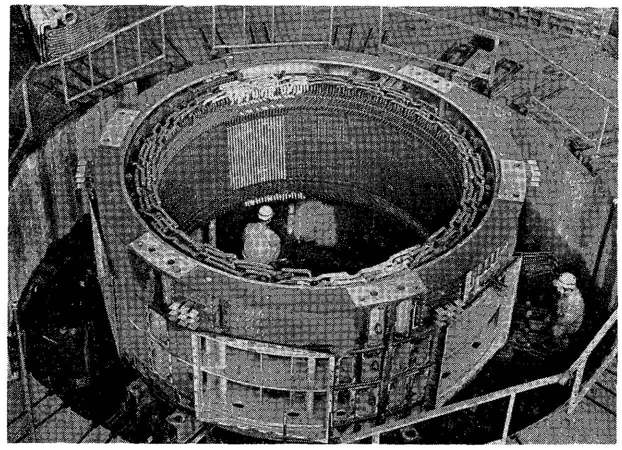

Fig. 2 Stator and connection of stator coils

Accordingly, the ratio of induced voltage becomes:

$$\frac{E_{18}}{E_{20}} = 0.865 \times 0.98 \times \frac{20}{18} = 0.942$$

The voltage ratio requested in this machine is $V_{18}/V_{20} = 0.955$, thus the voltage ratio and the induced voltage ratio are almost equal and the flux density of the magnetic circuit is the same at both poles. Generally about 5% voltage difference occurs at the receiving and transmitting ends so that if this connection method was applied to the polechange type in the pumping station, unlike this case being unlimited, magnetic material could be used fully at both poles. Furthermore, when it is operated as a motor at low speed and low head flux density lowers but amperage lowers simultaneously because the load itself becomes lighter at low speed.

Pole change of field winding is made by dividing the total poles into three groups: 1st, that in which polarity remains constant, 2nd, in which polarity changes, and 3rd, in which there is no excitation at 18 pole by a short circuit. Next by pulling out these three groups through 5 slip rings, the pole change is made using the 3-pole double throw switch as mentioned earlier. Though the 5 slip rings are fitted in five layers, inspection and renewal of the brushes is easy because of the position of the brush holders.

Both the change-over switch for stator winding and field winding are being installed in housing and the change-over is made by pneumatic control. It isn't necessary that the change-over of field winding be made while the machine is at rest but we adopted the above sequence feeling it could prevent accidents such as the open field at the loaded state. We have taken the elapsed time of the change-over as one of the starting conditions, and open field during operation is a condition for an emergency stop. Thus the change-over of both windings is made at no voltage and the switch, small in size, is simply installed in housing.

IV. CONSTRUCTIONS

Fig. 3 shows the sectional view of the generator-motor. The blade servo-motor, provided for in the Deriaz type pump turbine, was installed inside of the rotor center. The rotor is divided into the upper shaft, the rotor center, and the lower shaft. The crane load and lift were decreased because generally the center and lower shaft of the rotor are lifted as one body. The "Maglager" was fitted on the upper shaft and the blade serve-motor was affixed to the top of the machine.

In the following we describe the construction features.

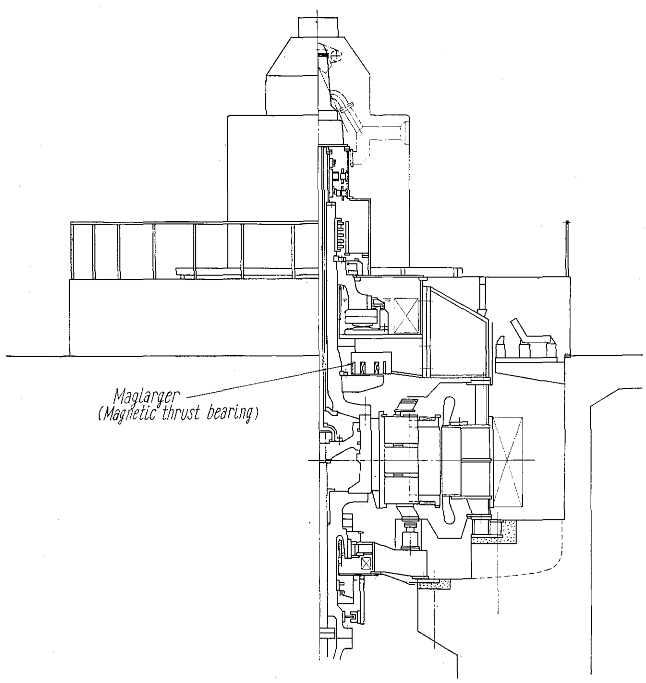

Fig. 3 Sectional view of generator-motor

1. Direct Coupling with Deriaz Type Pump-turbine

The machine is directly coupled to the Deriaz type turbine, however, this presents a problem, namely, that the gap between the runner and the discharge ring must be as small as possible in order to prevent the gap cavitation and lowering in efficiency.

As it is well known, having the blade sloped at its periphery in the Deriaz type pump turbine, the vertical shift of the shaft directly influences the gap of the runner. Roughly speaking, elongation is caused by the load of the shaft, or of the construction matter, and the temperature change of the shaft. To keep this displacement at a constant value the gap of the runner must always be measured and the up and down movement of the shaft must be controlled.

Many control methods have been proposed but it is difficult to control a shaft of over 100 tons while it is operating. Therefore, without providing a control device it is necessary to settle the gap as small as possible accurately confirming the real variation. In this machine the rigidity of the upper bracket has been strengthened and the deflection of thrust bearing has been taken smaller than usual, so we decided the runner gap to be 1.8 mm vertical. Because this 1.8 mm is of the running time, the gap should be settled at erection considering the difference during resting and running.

Regarding the shaft displacement we discussed the following factors:

1) A regular gap of 1.8 mm is to be obtained at full-load using "Maglager" of water thrust of 100 tons.
2) The runner does not contact by the break-down of bearing metal at full-load operations.
3) The runner does not contact on emergency when maximum water thrust is increased to about 150 tons.

Further, during the factory test, we carefully measured such things as deflection of bracket, deflection of thrust spring, and elongation of shaft and stationary parts due to temperature rise during operation. Concerning the latter elongation, it has been recognized experimentally that the temperature of the shaft is almost equal to the outlet-air temperature of the air cooler after a long run. The temperature of the stator frame is partially the same as the inlet-air temperature of the air cooler but on the average it is roughly the same as the mean value of the inlet and outlet air temperature of the air cooler.

Above we have described only the variations of runner gap; in addition it is necessary to explain the measuring instrument for the runner gap in operation.

The measuring instrument is fitted and finely adjusted on the lower bracket of the generator-motor. The detector of displacement consists of differential reactors, each reactor being fitted on and below the disc projecting from the shaft. The runner gap is detected by measuring the reactance change corresponding to the shaft displacement. Because the elongation of the pump turbine shaft itself is small the measurement at this disk provides sufficient accuracy. Further, when the gap was reduced below a certain limit, an emergency stop or alarm is ordered.

During observation it was noted that the shaft lowers only by the thickness of the white metal at break-down of the bearing metal, thus this thickness was lessened especially to facilitate lowering. Though this method is rather complex, thrust bearing itself operates as a stopper and is more reliable than other construction which prevents drop accidents.

2. Rotor Construction

As illustrated in *Fig. 4* the poleco nsists of 12 large poles and 16 small poles and is fitted on the rotor

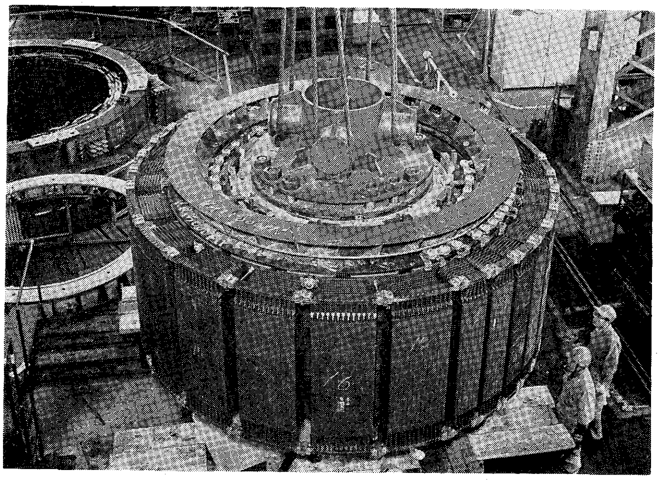

Fig. 4 Rotor

yoke through a dove-tail. The inner surface of the yoke is supported by 10 supporters of the rotor center. The rotor center and yoke are shrink fitted with an interference considering the effect of speed rise and the temperature difference between the rotor center and yoke while running. During our test for run-away speed the results for vibration were quite satisfactory.

3. Others

Thrust-bearing is an important factor for the reversible type generator-motor. We adopted the same type bearing as that of the generator-motor of 54.5 Mw already manufactured, namely, a reversible thrust-bearing of thrust load of 500 tons. This means, as shown in *Fig. 5*, pivots for each segment are located in the center of gravity and they are suitable for reversible operation.

Damper winding receives severe thermal deformation during motor starting, so special caution was paid to its construction. For example, the connecting plates in each damper winding are flexible, made of a copper alloy lamination, and have a curve at mid-point, thus heat deformation can be eliminated.

The upward thrust-bearing is fitted beneath the upper guide bearing. This bearing being faced with the thrust collar of the rotating part, is capable of withstanding the rotor float even when the upward water thrust floats the rotor.

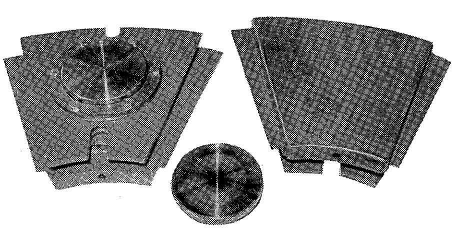

Fig. 5 Thrust bearing

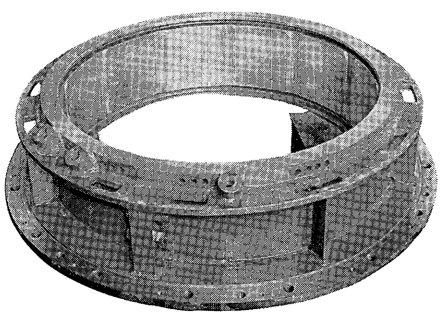

Fig. 6 Upper guide bearing

The oil groove for the guide bearing, as shown in *Fig. 6*, is arranged vertically taking into consideration the reversible operation.

On the arm of the lower bracket is a pressure oil jack which also serves as an air brake. This brake is the so-called double-cylinder system, having the cylinder for the high pressure oil jack on the bore side and the cylinder for the low pressure air brake on the outside. This type, serving both as an air brake and an oil jack, has been employed at several power stations and it is recognized as being more advantageous than the arrangement of separate air brakes and oil jacks.

V. TEST

Concerning our supply results of the Fuji system pole change type synchronous machine, wet ested a 200 kva 12/14 pole machine which supported the basic theory, and a 5000 kva 6/8 pole machine from which we gained information on loss, vibration and constructional problems. Thus we have completed the investigation concerning various factors. The test results of this machine, which was first manufactured as an actual pumping machine having an output several times larger, are interesting since they confirm the problems anticipated from the smaller machine and thus greater assurance can be given the user. Our tests included data which we had already measured.

1. Wave Shape of No-load Voltage and Wave Shape of 3 (2) Phase Short-circuit

Fig. 7 shows the wave shape of the magnetic field in air-gap and of the terminal voltage and current. The wave shape of the magnetic field is similar to the pole shape and has only a little drop in the small pole owing to the fringing of leakage-flux. The terminal voltage has wave forms near a pure sine wave, cancelling the higher harmonics component due to a well designed winding factor.

Table 2 shows the distortion of wave indicated in "Deviation factor" at JEC, "BTIF" at ASA, and "THF" at IEC, and a remarkable allowance can be seen in comparing the limited values in each standard,

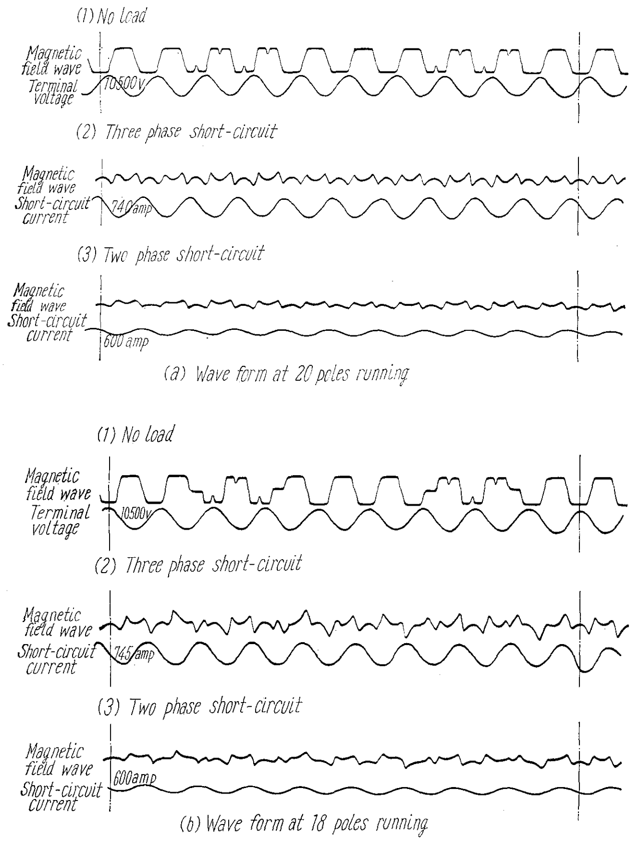

Fig. 7 **Wave form of no-load voltage, short-circuit current and magnetic field**

Table 2 **Distortion of wave form**

Poles / Indication	20	18	Rule
Deviation factor (%)	2.8	1.7	≦ 10
THF	0.773	0.63	< 1.5
BTIF	26.6	20.9	< 60

not being inferior to normal type synchronous machines.

The magnetic field in air-gap shows the complicated shape which superimposed on the magnetic field is excited by the pole on the magnetic field caused by armature reaction, but the wave shape of the short-circuit current itself is near that of the pure sine wave.

As stated above, the wave forms at both 18 and 20 poles are good especially at the 18 pole which has the irregular no-excitation pole. This is because the winding factor is selected so as to cancel the higher harmonics at 18 pole more than at 20 pole.

2. Efficiency

The efficiency of the pole change type is only a little less than that of a normal type machine. Of course, this lower value is out of question when compared to the improved efficiency of the hydraulic machine by pole change.

The reasons why efficiency lowers are: First, because an increase in machine size results in an increase in mechanical, core and copper losses; and secondly, a higher harmonics field in air-gap brings about the increase in core loss and stray-load loss. These two are closely connected with each other, that is, a better utilization factor of flux minimizes the surplus higher harmonics resulting in a decrease of a loss such as stray-load loss.

In the Fuji pole change system, having the best utilization factor of flux, a lowering in efficiency can hardly be observed. First of all, the mechanical loss which will increase proportionately with an increase of core length, barely increases because the bearing loss can be decreased remarkable by using "Maglager" not only at the start but during operation.

Core loss increases in hysteresis loss because the distorted magnetic field runs with a minor loop locally along B-H curve, and eddy loss due to higher harmonics is also taken into consideration. As shown in *Fig. 7*, the sink in the small pole should increase the hysteresis loss slightly, but we succeeded in minimizing the distortion of the magnetic field by the fringing effect, selecting the appropriate breadth and shape of the pole shoe. Eddy current loss is out of the question in this machine in which the higher harmonics field is extremely small.

Regarding pole-face loss, we can suppress it more than is possible in a normal machine by absorbing a higher harmonics component using a damper winding of suitable pitch. Therefore, as mentioned above, in our polechange synchronous machine an increase

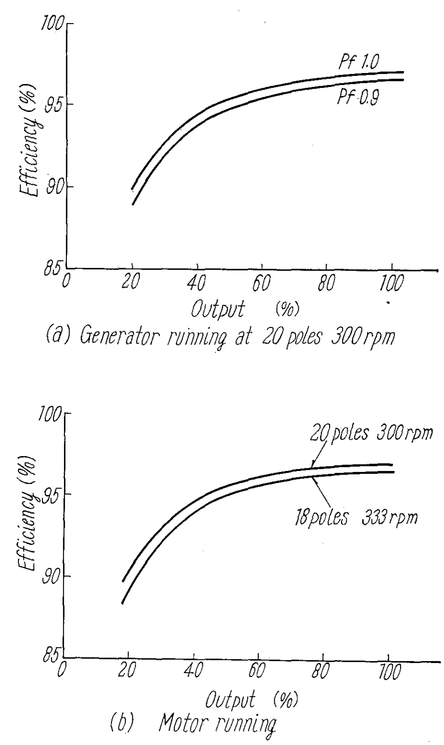

Fig. 8 **Efficiency curves**

in core loss could hardly be observed.

Stray-load loss is the eddy current loss produced in every place due to armature reaction and a higher harmonics component of the magnetic field. To prevent eddy loss in the coil end, a fan-shield was made of insulating material and a metal part was also located far of the coil. Also, the damper winding acts effectively so that only about 0.1% of rated output was increased due to higher harmonics and such increase is insignificant for overall efficiency.

Fig. 8 shows the test results measured in the machine including every increase in loss mentioned above. The figure in the efficiency curve shows the lowering of only about 0.2% of the total compared with the normal machine. This lower rate is of little value when we consider the merit of the hydraulic machine.

3. Various Kinds of Impedance and Time Constant

Table 3 shows impedance and time constant measured at the connection of 20 and 18 poles. It is evident that x_d and x_q differ at the 20 pole which shows saliency. However, as we have often reported, the saliency weakens at the 18 pole so there is almost no difference between x_d and x_q.

Table 3 **Impedance and time constant**

	20 Poles	18 Poles
x_d (%)	87	119
x_d' (%)	48	59.1
x_d'' (%)	16	19.1
x_2 (%)	15.5	19.1
x_q (%)	51.1	103
x_q'' (%)	15.0	18.9
x_o (%)	12.0	12.8
T_{do}' (sec)	6.08	6.1
T_d' (sec)	2.3	2.58

Remarks: Base impedance
1) 20 poles 11,000 v 997 amp
2) 18 poles 10,500 v 1159 amp

4. Motor Characteristics

1) Starting characteristics

Table 4 shows the starting torque and the starting current at half-voltage calculated from the result of the lock test. Though a special copper alloy was used for the damper winding in order to obtain a sufficiently large torque, counter torque itself is also large due to the construction of the thrust bearing. At an initial start after a long rest, which means that the oil film condition is at its worse and the static friction coefficient is larger than usual, counter torque is far above the starting torque. At this time,

Table 4 **Starting torque and current (when 50% voltage start)**

	18 Poles	20 Poles
Starting torque (t-m)	11.4	11.9
Starting current (amp)	2760	2700
Start (Mva)	25.1	24.6

Table 5 **Relation between current of "Maglager" and counter torque at motor start**

Maglarger current (amp)	Thrust load (t)	Counter torque (t-m)
130	4.5	2.4
110	20	4.7
87	43	7.7
70	61	11.1

if we use "Maglager" to diminish the load of thrust bearing, counter torque becomes smaller. *Table 5* shows the counter torque obtained as the function of bearing load, adjusting the exciting current of "Maglager." Referring to this table and the figure of starting torque, it can be observed that starting of the motor is possible at 60% of the exciting current which is necessary to lift the rotor.

2) Torque during low speed operation

To derive the torque-current curve during acceleration, low voltage should be applied externally to the motor under the natural acceleration and calculations made from the measured input and current. In this case there is a large acceleration constant, thus in using the above method sufficient accurate figures can be obtained.

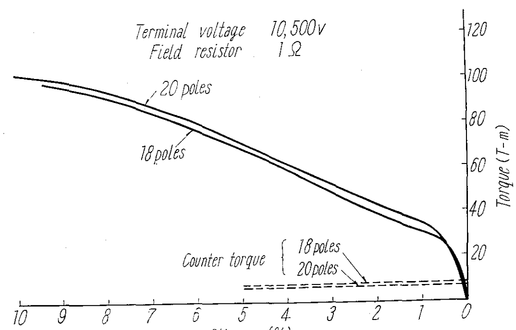

Fig. 9 Slip-torque characteristics

Torque characteristics, obtained by this method show that there is no abnormal torque aspect due to higher harmonics besides the fundamental wave component at the desired pole, therefore, smooth starting can be expected.

Fig. 9 shows the torque near synchronous speed which is necessary for pull-in. It may be understood that it is accelerated under the slip 1% as the induction motor even when it is accelerated at half-voltage.

5. Vibration

There may be concern about mechanical vibration due to higher harmonics. We tested vibration at each part including the local resonance.

The tested figure in half-amplitude at the connecting part of the upper bracket (in which vibration was relatively high) was 4.5 μ at 300 rpm and 8.5 μ at 333 rpm. These were almost equal at open-circuit rated voltage and short-circuit rated current. Both were under 10 μ and a relatively quiet operation was obtained, not displaying any special phenomenon compared to the normal machine.

VI. CONCLUSION

In this report we have discussed the characteristics, operation, construction and test results of the pol-change type salient-pole generator-motor at Kuromatagawa No. 2 power station, Electric Power Development Co., Ltd. As a result we can report that the anticipated data obtained experimentally with a small or medium machine was confirmed by this large machine, thus a good example is provided potential customers. It is also noteworthy that this larger machine is only 10% heavier than the usual machine.

We have made the most detailed test possible in order to obtain the fundamental data necessary for smooth on-site operations. Therefore, we believe that all of the characteristics of the machine were clarified. When the actual operation, coupled with the Deriaz type pump-turbine, is made on-site, all factors will be clarified and a detailed report will be forthcoming.

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